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# Research on Zero Carbon Design Method for Medical Buildings in Solar Enriched Areas – The Tibet Hospital of the West China Second University Hospital of Sichuan University

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The achievement of the green and low-carbon objectives of medical buildings in solar-enriched areas not only relates to the local people's aspirations in terms of enhanced medical environment but also reflects the regional endeavors toward zero-carbonization of the construction field in the west of China. In view of the scarcity of conventional energy in the regions and the high energy consumption of medical buildings, the overarching path of "Overall objectives and adjustment, segmentation strategy and optimization" is employed. A study on zero-carbon design methodology is conducted with respect to the multi-factor coupling of "Spatial Priority - Synergistic Optimization of Renewable Energy and Construction." The validation of the design methodology is carried out using the project of Tibet Hospital of West China Second Hospital of Sichuan University as an example. Based on the segmented optimization and co-optimization methods under the whole life cycle perspective, the optimal solution proposed in this study can achieve a 14.4 % reduction in energy consumption, a 10.5 % reduction in carbon emission, and a 4.6 % increase in the useful daylight illuminance.
Solar enriched area, Medical buildings, Zero carbon building, Architecture design, Technology path

## 1. Introduction

The impetus of the national dual carbon goal targets positions the building industry, one of the three primary sectors for carbon emissions in China, at a pivotal transition from energy-saving buildings to low-carbon buildings. Medical buildings, as an important carrier in healthcare provision, are integral to safeguarding human life and health. " Solar enriched areas " of the Qinghai-Tibet Plateau in China present an environment of high altitude, low pressure, and cold climate combined with hypoxia, which poses detrimental effects on human health (Luks, 2022). The total carbon emissions of medical institutions in China were ranked the second worldwide countries in 2022 (HCWH and ARUP, 2021). The most significant contributors to carbon emissions in the healthcare system were public hospitals (148 Mt, accounted for 47 %) (Wu, 2019). Promoting the zero-carbonization of medical buildings in solar-enriched areas and improving the medical environment would significantly impact society and confer environmental benefits.

There is yet limited discussion on the zero-carbon design method of medical buildings in solar-enriched areas. Medical buildings are characterized by mixed functional spaces with high demand for environmental quality and energy use intensity. On the one hand, embodied carbon emissions from building materials and equipment occupy a considerable proportion of solar-enriched areas, constrained by economic development, construction level, and transportation conditions. On the other hand, operational carbon emissions can be significantly reduced because electricity is primarily generated from renewable energy (NBSPRC, 2023), and accordingly, the grid emission factor could be significantly low. Under the influences of multiple factors, including local climate, building type, technological advancement, economic aspect, and energy resources, it is worth exploring how to achieve the goal of low carbon throughout the life cycle and zero carbon during operation for medical buildings in solar-enriched areas.

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## 2. Methods

Given the overarching objective of minimizing carbon emissions across the life cycle, strategies are prioritized in Eq(1). Accordingly, the guiding principle for strategy selection is prioritizing those substantially diminishing operational energy consumption per unit area, exhibiting broad applicability, ensuring a protracted service life, and embodied carbon minimum.

$$\Delta C_{LC,i} = \Delta C_{YX,i} - \Delta C_{YH,i} = \Delta EUI_i \cdot S_i \cdot DF_i \cdot EF - \Delta C_{YH,i} \quad (1)$$

In medical buildings in regions with abundant solar energy, implementing renewable energy sources confers four principal advantages: Firstly, the moderate height of these buildings ensures a substantial roof area suitable for solar installations (Cui et al., 2023). Secondly, the richness of the solar resource enhances photovoltaic efficiency, while reduced air pollution extends the operational life of the photovoltaic equipment. Additionally, the coincidence of peak energy demand with daylight hours optimizes solar energy utilization, minimizing wastage. Lastly, supportive local policies encourage the establishment of distributed photovoltaic power stations and provide the option for a "self-consumption plus feed-in" model, which aligns with sustainable energy practices.

The zero-carbon building design methodology proposed herein is an integrated, multi-element coupling approach emphasizing " Spatial Priority - Synergistic Optimization of Renewable Energy and Construction" as depicted in Figure 1. This methodology unfolds through the following sequential steps:

- Strategy Extraction: Identify zero-carbon design strategies influenced by multiple elements tailored to the climatic attributes of solar-rich regions and the specific type of medical facility.
- Segmental Optimization: Optimize sequentially at the levels of space, structure, and energy, prioritizing spatial form strategies to ascertain the annual energy consumption of the reference Building.
- Carbon Reduction Assessment: Ascertain each strategy's maximum carbon reduction potential and set the life cycle carbon reduction target, which serves as the benchmark for strategic prioritization.
- Synergistic Optimization Modeling: Construct a multi-objective optimization model that considers energy consumption, carbon reduction, cost, and daylighting.

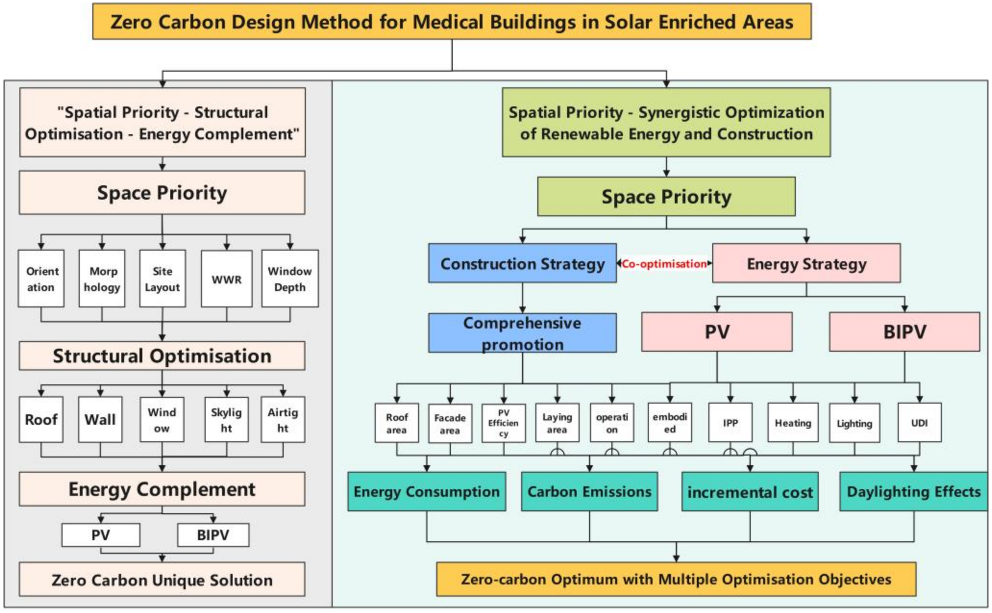


*Figure 1: Multi-factor coupled zero-carbon design method of Spatial Priority - Synergistic Optimization of Renewable Energy and Construction*

## 3. Results and Discussion

### 3.1 Case Study

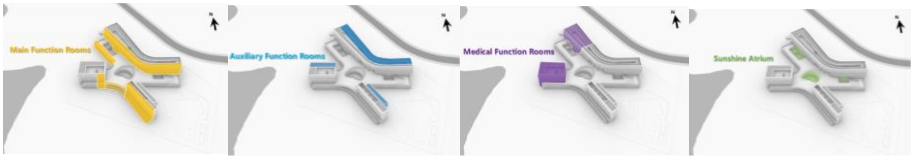
A case study was conducted on the Tibet Hospital of the West China Second University Hospital of Sichuan University. The hospital, a five-story structure, spans 32,171 m$^2$ of floor area above ground. As one of two national-level regional medical centers in Tibet, it plays a pivotal role in the region's overall development. Figure 3 displays the project design rendering.

*Figure 2: Project Design Rendering*

## 3.2 Segmental Optimization

### 3.2.1 Spatial Strategy

Following the strategic optimization sequence outlined in this paper, the initial phase prioritizes spatial strategies. Layout should fully consider the use of its characteristics, the main functional rooms are arranged in the south and west direction and other areas with sufficient sunshine. In the north direction, the auxiliary function rooms are mainly arranged, and for the operating rooms and equipment rooms of the medical department which do not need lighting, they are arranged in the interior of the building, and at the same time, the layout of the sunshine atrium and side court is utilized to create more heat-collecting and heat-storing and natural lighting conditions, so as to provide comfortable and healthy indoor environments for the doctors and the patients. Layout strategies for different functional rooms presents Figure 3.



*(a) Main function rooms (b) Auxiliary function rooms (c) Medical function rooms (d) Sunshine atrium*

*Figure 3: Layout strategies for different functional rooms*

In optimizing spatial form, the first step is to identify the key factors influencing building energy consumption and define their value ranges. These factors include building orientation, layout, window-to-wall ratios (WWR) for different orientations, window depth, and two additional factors, making a total of seven. The correlation between these factors and building energy consumption is assessed using the Pearson correlation coefficient evaluation method, as in Eq(2).

$$r(X,Y) = \frac{Cov(X,Y)}{\sqrt{Var[X]Var[Y]}} \qquad (2)$$

Where the correlation coefficient r(X,Y) takes values between -1 and 1, with strong correlation between 0.8 and 1, medium correlation between 0.5 and 0.8, and weak correlation below 0.5. The experimental outcomes are illustrated in Figure 4, revealing the factors that influence the heating energy consumption in order of descending impact: layout, window depth, WWR-S, WWR-W, WWR-N, WWR-E, and building orientation. Notably, the first four factors are the most critical, emphasizing the proper arrangement of functional spaces and maximizing solar heat gain by enhancing the WWR-S and WWR-W.These insights offer valuable guidance for zero-carbon design initiatives, particularly during the schematic design phase.

### 3.2.2 Construction Strategy

Construction strategies significantly impact both energy consumption and embodied carbon emissions. To identify the primary factors affecting carbon emissions throughout the lifecycle, a correlation analysis was conducted on 11 selected factors. These factors include the heat transfer coefficient and solar heat gain coefficient of the building envelope as well as airtightness. The result of this analysis is depicted in Figure 4a.
The order of importance of the size of the factors affecting energy consumption is firstly the airtightness, followed by the amount of heat gained by the external windows, thermal insulation of the external windows, and after considering the impact of the whole process of carbon emissions, measures such as increasing airtightness and the number of glazing cavities have a greater impact on the implied carbon emissions. Heat gain and insulation of the fenestration are critical. Based on the compliant baseline building, the maximum carbon control for the combination of building ontology strategies reaches 45.6 % as shown in Figure 4b, of which the spatial strategy

accounts for 21.6 %, which is an improvement of 8.0-14.2 % compared to different building types in other regions (Zhang et al, 2017).It is especially critical for the design of medical buildings in solar enriched areas.

(a) Spatial and construction strategy correlation analysis

(b) Distribution of carbon reduction potential of different strategies

*Figure 4: Analysis figures*

### 3.2.3 Energy Strategy

Analyzing the full life cycle, Eq (1) quantifies the maximum carbon reduction potential achievable through various construction and energy strategies. Figure 5 illustrates the $\Delta C_{YX,i}$ and $\Delta C_{YH,i}$ for these strategies across two scenarios: the project's maximum application area and per 1000 m² of the area in question. Notably, except for rooftop photovoltaics, the operational carbon savings from the remaining strategies fall short of compensating for the embodied carbon increase over the life cycle. The strategies' priority, based on carbon emissions $\Delta C_{LC,i}$, is as follows: PV, BIPV-S, BIPV-N, and then Construction Strategies.

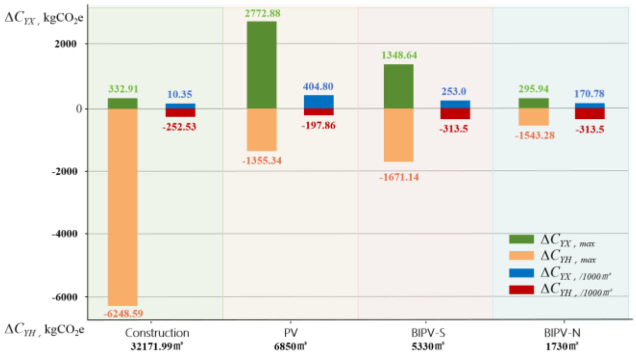


*Figure 5: Life cycle carbon reductions for construction and energy strategies*

The orientation of photovoltaic installations significantly influences energy consumption, life cycle carbon emissions, costs, and indoor lighting, with south-oriented installations offering higher power generation efficiency and lower embodied carbon due to reduced component area requirements. However, this orientation may negatively affect the thermal and lighting performance of south-facing functional rooms. In contrast, north facade installations have a less pronounced impact on the energy and lighting needs of north-facing auxiliary rooms. The analysis from Equation (1) indicates that a strategy optimization plan, tailored through segmented optimization, should be integrated with construction strategies across the building's life cycle, taking into account the combined effects of heating energy consumption and lighting.

### 3.3 Synergistic Optimization

### 3.3.1 Optimization Objectives

Synergistically optimizing the selection of four evaluation metrics, namely, energy consumption (EC) $f_{EC}(x)$, carbon emissions (CE) $f_{CE}(x)$ and incremental payback period (IPP) $f_{IPP}(x)$, as well as the proportion of area $f_{UDI}(x)$ with useful daylight illuminance ($UDI_{100\text{-}2000}$) that meets the standard.This optimization process is encapsulated within Eq(3).

$$min\, F\,(x) = f_{EC}(x), f_{CE}(x), f_{IPP}(x), f_{UDI}(x) \tag{3}$$

### 3.3.2 Decision Variables

The decision variables include 12 items that encompass the thermal performance of the roof, external walls, and fenestration, airtightness index, and the BIPV. A key constraint is the maximum allowable PV installation area on the project roof and facade. With the inclusion of an air source heat pump and a solar water heating system, the roof PV installation is capped at 6,200 m². The multi-objective optimization model is formulated in Eq(4).

s.t.

$$\begin{array}{ll} 0.30 \le RK \le 0.40 & 0.3 \le SHGC/W \le 0.7 \\ 0.40 \le WK \le 0.50 & 0.3 \le SHGC/N \le 0.7 \\ 1.6 \le CK/S \le 2.0 & 0.3 \le SHGC/E \le 0.7 \\ 1.6 \le CK/W \le 2.0 & 0.5 \le INF \le 1.5 \\ 1.6 \le CK/N \le 2.0 & BIPV = [0,1,2] \\ 1.6 \le CK/E \le 2.0 & Roof_1 \le 6200 \\ 0.3 \le SHGC/S \le 0.7 & Roof_2 \le 5550 \\ & Facade \le 1730 \end{array} \tag{4}$$

### 3.3.3 Optimization Results and Discussion

This study employed the Grasshopper plugin within the Rhino platform to execute multi-objective optimization calculations, leveraging the NSGA-II genetic algorithm. After 50 generations, the Pareto-optimal solutions across the four objectives were identified. These optimization outcomes were then organized and translated into a two-dimensional coordinate system, represented as a polyline on a parallel coordinates plot, as illustrated in Figure 6.

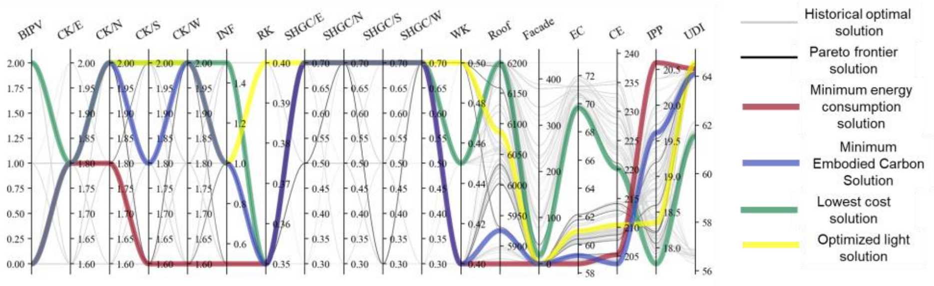


*Figure 6: Parallel Coordinates Plot of the Optimization Plan*

From an energy strategy perspective, under various optimization objectives, PV coverage consistently exceeds 95 %, nearly achieving a full coverage scenario. In the optimal energy consumption solution, full PV coverage is unnecessary to meet the operational zero-carbon target. The synergistic optimization outcomes align with the priority of PV strategies identified in segmented optimization. However, except for the cost-optimal solution, most synergistic optimization results do not favor BIPV, diverging from the segmented optimization's selection order of BIPV-S, BIPV-N, and construction strategies. This discrepancy can be attributed to two main factors as following.

Firstly, segmented optimization primarily considers the operational and embodied carbon impacts of individual strategies, often overlooking the interplay between construction and energy strategies. In solar-rich regions with low electricity carbon factors, the life cycle carbon emission optimal solution favors near-full rooftop coverage, no facade coverage, and optimized construction. Under smart lighting systems, the value of light transmission and heat gain in transparent enclosures surpasses insulation needs, making a high SHGC optimal for energy consumption, carbon emissions, cost, and daylighting. Non-transparent structures, such as roofs and external walls, utilize lightweight, locally produced insulation materials, resulting in a significantly lower change in $\Delta C_{LC}$ compared to BIPV constructions like cadmium telluride.

Secondly, the priority of BIPV-S over BIPV-N is influenced by the increased heating and lighting energy consumption in south-facing main functional rooms after PV installation, leading to higher operational carbon emissions. Historical optimal solutions show a 32.4 % increase in these energy consumptions for south-facing rooms, contrasting with the lesser impact on north-facing auxiliary rooms. Thus, synergistic optimization should prioritize BIPV-N installation, underscoring the significance of functional layout in building plans, particularly in medical facilities.

Considering the interdependencies among the four objectives, the project selects the optimal solution based on the lowest life cycle carbon emissions. Aside from a minor extension in the investment payback period due to reduced PV area, the other objectives have achieved varying degrees of optimization, as detailed in Table 1.

*Table 1: Results of Objective Decision for the Optimal Solution*

| | Reference Building | Optimal Solution | Improve Proportion |
|---|---|---|---|
| Energy Consumption (kWh/(m$^2$·a)) | 69.21 | 59.23 | 14.4 % |
| Carbon Emissions (kg CO$_2$/(m$^2$·a)) | 227.60 | 203.69 | 10.5 % |
| IPP (a) | 18.96 | 19.61 | -3.3 % |
| UDI (%) | 61.27 | 64.09 | 4.6 % |

## 4. Conclusions

This paper presents a comprehensive evaluation of resource endowments and constraints, proposing a zero-carbon design approach termed "spatial priority - construction and energy synergistic optimization" and a lifecycle strategy segmentation optimization evaluation method for medical buildings in solar-rich areas. A comprehensive optimal solution targeting operational zero-carbon was determined through a synergistic optimization design process under multi-objective coupling. Key conclusions from the study include:

(1) A segmented optimization method for evaluating the carbon reduction of individual strategies throughout the entire lifecycle has been proposed, establishing the priority principles for zero-carbon strategies from a full lifecycle perspective. Using $\Delta C_{LC}$ as the evaluation metric, the priority sequence for medical building strategies has been determined as PV, BIPV-S, BIPV-N, and construction strategies.

(2) A multi-objective optimization and multi-factor decision-making model has been constructed, yielding the comprehensive optimal solution under the operational zero-carbon target. The optimized solution can achieve a 14.4 % reduction in energy consumption, a 10.5 % reduction in carbon emissions over the life cycle, and a 4.6 % increase in the UDI.

### Nomenclature

*UDI* – useful daylight illuminance, %

$\Delta C_{LC,i}$ – carbon reduction in life cycle for the *i*-th strategy, kgCO$_2$e

$\Delta C_{YX,i}$ – operational carbon emission reduction for the *i*-th strategy, kgCO$_2$e

$\Delta C_{YH,i}$ – embodied carbon emissions increasement for the *i*-th strategy, kgCO$_2$e

$\Delta EUI_i$ – annual energy use intensity reduction per unit area achieved by the *i*-th strategy, kWh/(m$^2$·a)

$S_i$ – the *i*-th strategy area, m$^2$

$DF_i$ – the design service life of the *i*-th strategy, a

*EF* – the emission factor, kgCO$_2$/kWh

*Cov(X,Y)* - the covariance of X and Y

*Var[X] - the variance of X*

*WWR* - the window-to-wall ratio, -

*RK* – heat transfer coefficient of roof, W/(m$^2$·K)

*WK* – heat transfer coefficient of wall, W/(m$^2$·K)

*CK* – heat transfer coefficient of window, W/(m$^2$·K)

*SHGC* - solar heat gain coefficient, -

*PV* – rooftop photovoltaic, -

*BIPV* – building integrated PV, -

IPP – incremental payback period, a

*INF* – airtight of window, m$^3$/(m·h)

*NSGA* – non-dominated sorting genetic algorithms

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